REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE April 1996	3. REPORT TYPE AND DATES COVERED Final 3/1/93 - 2/29/96
4. TITLE AND SUBTITLE Hierarchical Adaptive Modeling	5. FUNDING NUMBERS Grant No. F49620-93-1-0184	
6. AUTHORS(S) Ahmed K. Noor	AFOSR-TR-96	
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) University of Virginia Department of Civil Engineering and Applied Mechanics School of Engineering and Applied Science Thornton Hall Charlottesville, VA 22903-2442	8. PER[FORMING ORGANIZATION] REI[PORT NUMBER] 0308 UVA/.	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES) Airforce Office of Scientific Research 110 Duncan Avenue, Suite B115 Bolling AFB, DC 20332-0001 NA	10. SPONSORING/MONITORING AGENCY REPORT NUMBER 93-1-0184	
11. SUPPLEMENTARY NOTES The view, opinion, and/or findings contained in the report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.		
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited	12b. DISTRIBUTION CODE	

13. ABSTRACT *(Maximum 200 words)*

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19960624 245

14. SUBJECT TERMS	15. NUMBER OF PAGES 19
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (890104 Draft)
Prescribed by ANSI Std. 239-18
298-01

Final Report

AFOSR Grant F49620-93-1-0184

HIERARCHICAL ADAPTIVE MODELING

March 1, 1993 - February 29, 1996

Submitted to:

Air Force Office of Scientific Research
Building 410
Bolling Air Force Base
Washington, D.C. 20332-6448

Attention:

Dr. Walter Jones

Submitted by:

Ahmed K. Noor
Ferman W. Perry Professor of
Aerospace Structures and Applied Mechanics

Department of Civil Engineering
SCHOOL OF ENGINEERING AND APPLIED SCIENCE
UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA

Report No.
April 1996

Copy No.

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ABSTRACT

Computational procedures are developed for evaluating the hierarchical sensitivity coefficients of the nonlinear static and dynamic frictional contact response of composite structures. The hierarchical sensitivity coefficients measure the sensitivity of the response to three sets of interrelated parameters; namely, panels (or shells), layer and micromechanical parameters. The computational procedure is applied to the nonlinear static, postbuckling and dynamic impact response of composite shells and panels, as well as to sandwich structures with composite face sheets.

RESEARCH OBJECTIVES

The objectives of the proposed study was to develop effective hierarchical adaptive modeling strategies for predicting the response and failure of complex structures. The strategies aimed at simulating phenomena occurring at disparate spatial and time scales using reasonable computer resources. The strategies are based on using multiple mathematical models in different regions of the structure to take advantage of efficiencies gained by matching the model to the expected response in each region. To achieve the full potential of hierarchical modeling, minimal reliance will be made on *a priori* assumptions about the response. This is accomplished by adding adaptivity to the strategy. The key tasks of the research are the following:

1. Rational selection of a set of nested mathematical models for different regions, and discretization techniques for use in conjunction with the mathematical models. The nesting can mathematically be expressed by using operator splitting techniques.

2. Simulation of local phenomena through global/local methodologies.

3. Automated (or semiautomated) coupling of different mathematical/discrete models.

4. Criteria for adaptive refinement (or derefinement) of the mathematical and discrete models.

5. Stable and efficient iterative process and numerical algorithms for use in conjunction with adaptive model refinement.

Application of the strategies developed will be made to: a) high-temperature structures with temperature-sensitive materials; and b) smart materials/structures with strong coupling between mechanical, thermal, electrical and magnetic fields.

RESEARCH ACCOMPLISHMENTS

The results of the research conducted under this grant are included in twelve publications. Five technical presentations were made based on the studies made under this grant. The list of presentations is given in Appendix II. The abstracts of these papers are given in Appendix I. The research activities can be grouped into two categories, described subsequently. Also, a state-of-the-art review was conducted on the computational models for sandwich plates and shells (Ref. 13).

1. Sensitivity Analysis of Frictional Contact Response of Axisymmetric Composite Structures

Computational procedures have been developed for evaluating the sensitivity coefficients of the static and dynamic frictional contact responses of axisymmetric composite structures. A displacement finite element model is used for the spatial discretization. The normal contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with the fundamental unknowns consisting of the nodal displacements, and the Lagrange multipliers associated with the contact conditions. The Lagrange multipliers are allowed to be discontinuous at interelement boundaries. Tangential contact conditions are incorporated by using a penalty method in conjunction with the classical Coulomb's friction model. For dynamic impact problems, the temporal integration is performed by using Newmark's scheme. The Newton-Raphson iterative scheme is used for the solution of the resulting nonlinear algebraic equations, and for the determination of the contact region, contact conditions (sliding or sticking), and the contact pressures. The sensitivity coefficients are evaluated by using a direct differentiation approach. Numerical results are presented for the static and dynamic frictional contact of a composite spherical cap and a composite cylinder both pressed against (or impacting) a rigid plate (see Refs. 6 and 10).

2. <u>Hierarchical Sensitivity Coefficients of Nonlinear and Postbuckling Responses of Composite Panels</u>

The nonlinear and postbuckling response characteristics of laminated composite structures are dependent on a hierarchy of interrelated parameters including laminate, layer and micromechanical (fiber, matrix and interface/interphase) parameters. A study of the sensitivity of the response to variations in each of these parameters provides an insight into the importance of the parameters and helps in the development of new materials to meet certain performance requirements.

A computational procedure has been developed for evaluating the sensitivity coefficients of the nonlinear and postbuckling responses with respect to three sets of parameters; namely, panels, layer and micromechanical parameters. The panel parameters include the extensional stiffnesses, bending stiffnesses, bending-extensional coupling stiffnesses, transverse shear stiffnesses, and the thermal effects appearing in the laminate constitutive relations. The layer parameters include the individual layer properties: Young's moduli, shear moduli, Poisson's ratios, coefficients of thermal expansion, fiber orientation angle, and layer thickness. The micromechanical parameters include fiber, matrix and interface/interphase moduli; and fiber and matrix volume fractions.

The computational procedure consists of evaluating the sensitivity coefficients with respect to each of the panel (or laminate) stiffnesses; and then generating the sensitivity coefficients with respect to each of the layer and micromechanical parameters as linear combinations of them.

The procedure has been applied to flat and curved panels with and without cutouts, subjected to combined edge shortening, edge shear and uniform temperature change (see Refs. 4, 5, 7, 9, 11 and 12).

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2. Noor, A. K. and Kim, Y. H., "Effect of Mesh Distortion on the Accuracy of Transverse Shear Stresses and Their Sensitivity Coefficients in Multilayered Composites," *Mechanics of Composite Materials and Structures*, Vol. 2, No. 1, March 1995, pp. 49-69.

3. Karaoglan, L. and Noor, A. K., "Sensitivity Analysis of Frictional Contact Response of Axisymmetric Composite Structures," *Computers and Structures*, Vol. 55, No. 6, June 1995, pp. 937-954.

4. Noor, A. K., Starnes, J. H., Jr. and Peters, J. M., "Nonlinear and Postbuckling Responses of Curved Composite Panels with Cutouts," *Composite Structures*, Vol. 27, No. 10, 1995, pp. 1269.

5. Noor, A. K., "Recent Advances in the Sensitivity Analysis for the Thermomechanical Postbuckling of Composite Panels," *ASCE Journal of Engineering Mechanics*, Vol. 122, No. 4, April 1996, pp. 300-307.

6. Karaoglan, L. and Noor, A. K., "Dynamic Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures," *Computer Methods in Applied Mechanics and Engineering*, Vol. 128, Nos. 1-2, 1995, pp. 169-190.

7. Noor, A. K. and Kim, Y. H., "Buckling and Postbuckling of Composite Panels with Cutouts Subjected to Combined Edge Shear and Temperature Change," *Computers and Structures* (to appear).

8. Karaoglan, L. and Noor, A. K., "Assessment of Temporal Integration Schemes for the Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures," *Computer Methods in Applied Mechanics and Engineering* (to appear).

9. Kim, Y. H. and Noor, A. K., "Buckling and Postbuckling of Composite Panels with Cutouts Subjected to Combined Loads," *Finite Elements in Analysis and Design* (to appear).

10. Pollock, G. D. and Noor, A. K., "Sensitivity Analysis of the Contact/Impact Response of Composite Structures," *Computers and Structures* (to appear).

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12. Noor, A. K., Starnes, J. H., Jr. and Peters, J. M., "Thermomechanical Buckling and Postbuckling Responses for Composite Panels with Skewed Stiffeners," *Proceedings of the 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 15-17, 1996, Salt Lake City, UT (to appear).

13. Noor, A. K., Burton, W. S. and Bert, C. W., "Computational Models for Sandwich Panels and Shells," *Applied Mechanics Reviews*, Vol. 49, No. 3, March 1996, pp. 155-199.

Appendix I

SENSITIVITY ANALYSIS FOR THE DYNAMIC RESPONSE OF VISCOPLASTIC SHELLS OF REVOLUTION

Makarand Kulkarni and Ahmed K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia 23681

Abstract

A computational procedure is presented for evaluating the sensitivity coefficients of the viscoplastic dynamic axisymmetric response of shells of revolution. The analytical formulation is based on Reissner's large-deformation shell theory with the effects of transverse shear deformation, rotatory inertia and moments turning around the normal to the middle surface included. The material model is chosen to be isothermal viscoplasticity, and an associated flow rule is used with a von-Mises effective stress. A mixed formulation is used with the fundamental unknowns consisting of six stress resultants, three generalized displacements and three velocity components.

Finite element models, with discontinuous stress resultants at the element interfaces, are used for the spatial discretization. The temporal integration is performed by using an explicit central difference scheme (leap-frog method) with an implicit stress update. The sensitivity coefficients are evaluated using a direct differentiation approach. Numerical results are presented for spherical cap subjected to step loading and circular plate subjected to impulsive loading. The sensitivity coefficients are generated by evaluating the derivatives of the response quantities with respect to the thickness, mass density, Young's modulus, and two of the material parameters characterizing the viscoplastic response. Time histories of the response and sensitivity coefficients, along with spatial distributions of these quantities at selected times are presented.

Published: *Computers and Structures, Vol. 55, No. 6, June 1995, pp. 955-970.*

EFFECT OF MESH DISTORTION ON THE ACCURACY OF TRANSVERSE SHEAR STRESSES AND THEIR SENSITIVITY COEFFICIENTS IN MULTILAYERED COMPOSITES

Ahmed K. Noor and Yong H. Kim
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia 23681

ABSTRACT

A study is made of the effect of mesh distortion on the accuracy of transverse shear stresses and their first-order and second-order sensitivity coefficients in multilayered composite panels subjected to mechanical and thermal loads. The panels are discretized by using a two-field degenerate solid element, with the fundamental unknowns consisting of both displacement and strain components, and the displacement components having a linear variation throughout the thickness of the laminate. A predictor-corrector computational procedure is used for evaluating the transverse shear stresses. The predictor phase can be conveniently divided into two steps. The first step consists of using a superconvergent recovery technique for evaluating the in-plane stresses in the different layers. In the second step, the transverse shear stresses are evaluated by using piecewise integration, in the thickness direction, of the three-dimensional equilibrium equations. In the corrector phase the thickness distribution of the displacement components is calculated by integrating the three-dimensional stress-displacement relations and using them to improve the predictions of the in-plane and transverse stresses. The same predictor-corrector procedure is used for evaluating the sensitivity coefficients of transverse shear stresses. Numerical results are presented showing no noticeable degradation in the accuracy of the in-plane stresses and their sensitivity coefficients with mesh distortion. However, such degradation is observed for the transverse shear stresses and their sensitivity coefficients. The standard of comparison is taken to be the exact solution of the three-dimensional thermoelasticity equations of the panel.

Published: *Mechanics of Composite Materials and Structures,* Vol. 2, No. 1, March 1995, pp. 49-69.

SENSITIVITY ANALYSIS OF FRICTIONAL CONTACT RESPONSE OF AXISYMMETRIC COMPOSITE STRUCTURES

L. Karaoglan and A. K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia

Abstract

A computational procedure is presented for evaluating the sensitivity coefficients of the static frictional contact response of axisymmetric composite structures. The structures are assumed to consist of an arbitrary number of perfectly bonded homogeneous anisotropic layers. The material of each layer is assumed to be hyperelastic, and the effect of geometric nonlinearity is included. The sensitivity coefficients measure the sensitivity of the response to variations in different material, lamination and geometric parameters of the structure. A displacement finite element model is used for the discretization. The normal contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with the fundamental unknowns consisting of nodal displacements, and Lagrange multipliers associated with the contact conditions. The Lagrange multipliers are allowed to be discontinuous at interelement boundaries. Tangential contact conditions are incorporated by using a penalty method in conjunction with the classical Coulomb's friction model. The Newton-Raphson iterative scheme is used for the solution of the resulting nonlinear algebraic equations, and for the determination of the contact region, contact conditions (sliding or sticking), and the contact pressures. The sensitivity coefficients are evaluated by using a direct differentiation approach. Numerical results are presented for the friction contact of a composite spherical cap pressed against a rigid plate.

Published: *Computers and Structures, Vol. 55, No. 6, June 1995, pp. 937-954.*

NONLINEAR AND POSTBUCKLING RESPONSES OF CURVED COMPOSITE PANELS WITH CUTOUTS

Ahmed K. Noor , James H. Starnes, Jr.*
and Jeanne M. Peters
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia 23681

Abstract

The results of a detailed study of the nonlinear and postbuckling responses of curved unstiffened composite panels with central circular cutouts are presented. The panels are subjected to applied edge displacements and temperature changes. The analysis is based on a first-order shear-deformation Sanders-Budiansky type theory with the effects of large displacements, moderate rotations, transverse shear deformation and laminated anisotropic material behavior included. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the nonlinear response to variations in three sets of interrelated parameters; namely, the panel stiffnesses, the material properties of the individual layers, and the material properties of the constituents (fibers, matrix, interface and interphase). Numerical results are presented for cylindrical panels with central circular cutouts and subjected to edge shortening and uniform temperature change. The results show the effects of variations in the panel curvature, hole diameter, laminate stacking sequence and fiber orientation, on the nonlinear and postbuckling panel responses, and their sensitivity to changes in the various panel, layer and micromechanical parameters.

*NASA Langley Research Center, Hampton, VA

Published: *Composite Structures*, Vol. 27, No. 10, 1995, pp. 1269.

RECENT ADVANCES IN THE SENSITIVITY ANALYSIS FOR THE THERMOMECHANICAL POSTBUCKLING OF COMPOSITE PANELS

Ahmed K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia 23681

Abstract

Three recent developments in the sensitivity analysis for the thermomechanical postbuckling response of composite panels are reviewed. The three developments are: effective computational procedure for evaluating hierarchical sensitivity coefficients of the various response quantities with respect to the different laminate, layer and micromechanical characteristics; application of reduction methods to the sensitivity analysis of the postbuckling response; and accurate evaluation of the sensitivity coefficients of transverse shear stresses. Sample numerical results are presented to demonstrate the effectiveness of the computational procedure presented. Some of the future directions for research on sensitivity analysis for the thermomechanical postbuckling response of composite and smart structures are outlined.

Published: *Journal of Engineering Mechanics*, Vol. 122, No. 4, April 1996, pp. 300-307.

DYNAMIC SENSITIVITY ANALYSIS OF FRICTIONAL CONTACT/IMPACT RESPONSE OF AXISYMMETRIC COMPOSITE STRUCTURES

L. Karaoglan and A. K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia

Abstract

A computational procedure is presented for evaluating the sensitivity coefficients of the frictional contact/impact response of axisymmetric composite structures. The structures are assumed to consist of an arbitrary number of perfectly bonded homogeneous anisotropic layers. The material of each layer is assumed to be hyperelastic, and the effect of geometric nonlinearity is included. The sensitivity coefficients measure the sensitivity of the response to variations in different material, lamination and geometric parameters of the structure. A displacement finite element model is used for the spatial discretization. The normal contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with the fundamental unknowns consisting of nodal displacements, and Lagrange multipliers associated with the contact conditions. The Lagrange multipliers are allowed to be discontinuous at interelement boundaries. Tangential contact conditions are incorporated by using a penalty method in conjunction with the classical Coulomb's friction model. The temporal integration is performed by using Newmark's scheme. The Newton-Raphson iterative scheme is used for the solution of the resulting nonlinear algebraic equations, and for the determination of the contact region, contact conditions (sliding or sticking), and the contact pressures. The sensitivity coefficients are evaluated by using a direct differentiation approach. Numerical results are presented for the frictional contact/impact response of a composite spherical cap impacting on a rigid plate.

Published: *Computer Methods in Applied Mechanics and Engineering*, Vol. 128, Nos. 1-2, 1995, pp. 169-190.

BUCKLING AND POSTBUCKLING OF COMPOSITE PANELS WITH CUTOUTS SUBJECTED TO COMBINED EDGE SHEAR AND TEMPERATURE CHANGE

Ahmed K. Noor and Yong H. Kim
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, VA 23681

ABSTRACT

The results of a detailed study of the buckling and postbuckling responses of composite panels with central circular cutouts are presented. The panels are subjected to combined edge shear and temperature change. The panels are discretized by using a two-field degenerate solid element with each of the displacement components having a linear variation throughout the thickness of the panel. The fundamental unknowns consist of the average mechanical strains through the thickness and the displacement components. The effects of geometric nonlinearities and laminated anisotropic material behavior are included.

The stability boundary, postbuckling response and the hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in the panel stiffnesses, and the material properties of both the individual layers and the constituents (fibers and matrix). Numerical results are presented for composite panels with central circular cutouts subjected to combined edge shear and temperature change, showing the effects of variations in the hole diameter, laminate stacking sequence and fiber orientation, on the stability boundary and postbuckling response and their sensitivity to changes in the various panel parameters.

To be Published: *Computers and Structures*

Assessment of Temporal Integration Schemes for the Sensitivity Analysis of Frictional Contact/Impact Response of Axisymmetric Composite Structures

L. Karaoglan and A. K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, Virginia

Abstract

An assessment is made of three temporal integration schemes for the sensitivity analysis of the frictional contact/impact response of axisymmetric composite structures. The structures considered consist of an arbitrary number of perfectly-bonded homogeneous anisotropic layers. The material of each layer is assumed to be hyperelastic, and the effect of geometric nonlinearity is included. Sensitivity coefficients measure the sensitivity of the response to variations in the different material, lamination and geometric parameters of the structure.

A displacement finite element model is used for the spatial discretization. Normal contact conditions are incorporated into the formulation by using a perturbed Lagrangian approach with fundamental unknowns consisting of both the nodal displacements and the Lagrange multipliers associated with the contact conditions. The Lagrange multipliers are allowed to be discontinuous at interelement boundaries. Tangential contact conditions are incorporated by using either a penalty method or a Lagrange multiplier technique, in conjunction with the classical Coulomb's friction model. The three temporal integration schemes considered are: the implicit Newmark and Houbolt schemes, and the explicit central difference method. In the case of the implicit methods, the Newton-Raphson iterative technique is used for the solution of the resulting nonlinear algebraic equations, and for the determination of the contact region, contact conditions (sliding or sticking), and the contact pressures. Sensitivity coefficients are evaluated by using a direct differentiation approach in conjunction with the incremental equations. Numerical results are presented for the frictional contact of a composite spherical cap impacting a rigid plate, showing the effects of each of the following factors on the accuracy of the predicted response and sensitivity coefficients: (a) incorporating the normal contact conditions, (b) the magnitude of the penalty parameter in the normal direction (for the perturbed Lagrangian method), and (c) the time step size for the response and the sensitivity analyses.

To be Published: *Computer Methods in Applied Mechanics and Engineering*

BUCKLING AND POSTBUCKLING OF COMPOSITE PANELS WITH CUTOUTS SUBJECTED TO COMBINED LOADS

Yong H. Kim and Ahmed K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, VA 23681

ABSTRACT

A detailed study is made of the buckling and postbuckling responses of composite panels with central circular cutouts subjected to various combinations of mechanical and thermal loads. The panels are discretized by using a two-field degenerate solid element with each of the displacement components having a linear variation through the thickness of the panel. The fundamental unknowns consist of the average mechanical strains through the thickness, and the displacement components. The effects of geometric nonlinearities and laminated anisotropic material behavior are included.

The stability boundary, postbuckling response and the hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in the panel stiffnesses, and the material properties of both the individual layers and the constituents (fibers and matrix). Extensive numerical results are presented for composite panels with central circular cutouts subjected to combined edge shortening, edge shear and temperature change. The results show the effects of variations in the hole diameter; the aspect ratio of the panel; the laminate stacking sequence and the fiber orientation on the stability boundary, postbuckling response and sensitivity coefficients.

To be published: *Finite Elements in Analysis and Design*

Sensitivity Analysis of the Contact/Impact Response of Composite Structures

Gerry D. Pollock Ahmed K. Noor
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, VA

Introduction

Concerns over crash survivability and related issues have prompted considerable work in the realistic modeling of contact-impact events. Due to its versatility, the finite element method continues to receive the most attention in the development of contact-impact algorithms. In recent years, the importance of frictional phenomena has been emphasized and has resulted in the inclusion of friction models in most algorithms. The current state of contact-impact technology is reviewed in a recent survey paper [1] and a monograph [2] by Zhong, et al.

To be published: *Computers and Structures*

Nonlinear and Postbuckling Analyses of Curved Composite Panels Subjected to Combined Temperature Change and Edge Shear

Ahmed K. Noor and Jeanne M. Peters
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, VA

Abstract

The results of a detailed study of the nonlinear and postbuckling responses of curved unstiffened composite panels with central circular cutouts are presented. The panels are subjected to uniform temperature change and an applied in-plane edge shear loading. The analysis is based on a first-order shear-deformation Sanders-Budiansky type theory with the effects of large displacements, moderate rotations, transverse shear deformation and laminated anisotropic material behavior included. A mixed formulation is used with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated.

Numerical results are presented for cylindrical panels with central circular cutouts and subjected to uniform temperature change and an applied in-plane edge shear loading. The results show the effects of variations in the panel curvature, hole diameter, laminate stacking sequence and fiber orientation, on the nonlinear and postbuckling panel responses, and their sensitivity to changes in the various panel, layer and micromechanical parameters.

To be published: *Computers and Structures*

THERMOMECHANICAL BUCKLING AND POSTBUCKLING RESPONSES OF COMPOSITE PANELS WITH SKEWED STIFFENERS

Ahmed K. Noor,* James H. Starnes, Jr.** and Jeanne M. Peters***
Center for Computational Structures Technology
University of Virginia
NASA Langley Research Center
Hampton, VA 23681

Abstract

The results of a detailed study of the buckling and postbuckling responses of composite panels with skewed stiffeners are presented. The panels are subjected to applied edge displacements and temperature changes. A first-order shear-deformation geometrically nonlinear shallow-shell theory that includes the effects of laminated anisotropic material behavior is used to model each section of the stiffeners and the skin. A mixed formulation is used in the analysis with the fundamental unknowns consisting of the generalized displacements and the stress resultants of the panel. The nonlinear displacements, strain energy, transverse shear stresses, transverse shear strain energy density, and their hierarchical sensitivity coefficients are evaluated. The hierarchical sensitivity coefficients measure the sensitivity of the buckling and postbuckling responses to variations in three sets of interrelated parameters; namely, the panel stiffnesses; the effective material properties of the individual layers; and the constituent material parameters (fibers, matrix, interface and interphase). Numerical results are presented for rectangular panels with open section I-stiffeners, subjected to edge shortening and uniform temperature change.

*Professor of Aerospace Structures and Applied Mechanics, and Director, Center for Computational Structures Technology, University of Virginia, Fellow AIAA.
**Head, Structural Mechanics Branch, Fellow AIAA.
***Senior Programmer Analyst, Center for Computational Structures Technology, University of Virginia

To be Published: *Proceedings of the 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 15-17, 1996, Salt Lake City, UT

COMPUTATIONAL MODELS FOR SANDWICH PANELS AND SHELLS

Ahmed K. Noor and W. Scott Burton
Center for Advanced Computational Technology
University of Virginia
NASA Langley Research Center
Hampton, VA

and

Charles W. Bert
School of Aerospace and Mechanical Engineering
University of Oklahoma
Norman, OK

ABSTRACT

The focus of this review is on the hierarchy of computational models for sandwich plates and shells, predictor-corrector procedures, and the sensitivity of the sandwich response to variations in the different geometric and material parameters. The literature reviewed is devoted to the following application areas: heat transfer problems; thermal and mechanical stresses (including boundary layer and edge stresses); free vibrations and damping; transient dynamic response; bifurcation buckling, local buckling, face-sheet wrinkling and core crimping; large deflection and postbuckling problems; effects of discontinuities (e.g., cutouts and stiffeners), and geometric changes (e.g., tapered thickness); damage and failure of sandwich structures; experimental studies; optimization and design studies. Over 800 relevant references are cited in this review, and another 559 references are included in a supplemental bibliography for completeness. Extensive numerical results are presented for thermally stressed sandwich panels with composite face sheets showing the effects of variation in their geometric and material parameters on the accuracy of the free vibration response, and the sensitivity coefficients predicted by eight different modeling approaches (based on two-dimensional theories). The standard of comparison is taken to be the analytic three-dimensional thermoelasticity solutions. Some future directions for research on the modeling of sandwich plates and shells are outlined.

Published: *Applied Mechanics Reviews*, Vol. 49, No. 3, March 1996, pp. 155-199

APPENDIX II - PRESENTATIONS

1. Noor, A. K., "Nonlinear and Postbuckling Responses of Curved Composite Panels with Cutouts," 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, New Orleans, LA, April 10-13, 1994.
2. Noor, A. K., "Recent Advances in the Sensitivity Analysis for the Thermomechanical Postbuckling of Composite Panels," Second Thermal Structures Conference, University of Virginia, Charlottesville, Oct. 18-20, 1994.
3. Noor, A. K., "Sensitivity Analysis for the Dynamic Response of Viscoplastic Shells of Revolution," ASME 1994 International Mechanical Engineering Congress and Exposition, Chicago, IL, Nov. 6-11, 1994.
4. Noor, A. K."Thermomechanical Buckling and Postbuckling Responses for Composite Panels with Skewed Stiffeners," 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Salt Lake City, UT, April 15-17, 1996.